Double Shell Implosions in the Inertial-Confinement Fusion Program

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Introduction

The National Ignition Facility (NIF),[1] a large laser presently under construction at the Lawrence Livermore National Laboratory, is designed to produce 1.8 MJ of 0.35-μm light in a 500-TW, temporally shaped, laser pulse for defense applications and inertial-confinement fusion (ICF) ignition. The possibility of capsule ignition and gain at NIF, given the laser energy and power available, is far from a certainty and requires further laboratory experimentation and theoretical simulation to remove as many uncertainties as possible to reduce the risk of failure. Fusion ignition and gain require that the laser-driven implosion create a fuel region of sufficient size, density, and temperature that the fusion burn wave becomes self-sustaining. This requires deposition of the charged fusion products created by the burn within the high-density core to continue to heat the core despite competing energy-loss mechanisms.

Current Target Design

Such a self-sustained fusion burn is easiest to obtain using a deuterium-tritium (DT) fuel mixture. For DT fuel, the requirements for a self-sustained burn are that the ion temperature be of order 20 keV and that the density be high enough that the DT-reaction-produced alpha particles deposit their energy inside the fuel rather than escaping the fuel region. A density-radius product of a few g/cm^2 satisfies this local-deposition requirement. At NIF, rather than producing these conditions in a uniform volume (which would require a laser energy on the order of 100 MJ), the mainline capsule design employs a concept known as "hot-spot" ignition. In this concept, a small fraction of the fuel mass is ignited in a central hot spot, and then a thermonuclear burn wave propagates outward into the surrounding, lower-temperature, compressed fuel to produce a significant fusion yield.[1]

The production of such a central hot spot, with sufficient fuel at sufficient temperature to ignite and burn a reasonable fraction of the available fuel is believed to require cryogenic targets. A solid DT ice layer of order 100 microns thick held inside a thin CH or beryllium shell is required in order to contain enough fuel to ignite and at the same time not break under the extreme pressure that would be present for such a fuel load, if the target were at room temperature. This requires a cryogenic target-manipulation system, which implies a very complex engineering effort. Additionally, the inner surface of the DT ice layer must remain very uniform so that Rayleigh-Taylor instabilities, seeded by any inner surface nonuniformity, do not grow to a large enough amplitude during the final deacceleration phase of the implosion to cause the target to break up and the burn to be disrupted. Both of these requirements constitute significant unknowns relative to successful ignition using the cryogenic-point design target as currently envisioned.

A Double-Shell Target

If a target could be designed that could operate at room temperature with an adequate fuel load to ignite, it would provide a valuable alternative to the cryogenic-point design. If such a target were also able to operate with a simple square temporal power history out of the laser, rather than the severely shaped laser power pulse required for the cryogenic-point design target, that would be a significant additional advantage. A set of double-shell target designs that have been under investigation for the past several years by Los Alamos National Laboratory constitutes such a target. The physics goal of the double-shell implosion campaign, beginning at the NOVA laser at Lawrence Livermore National Laboratory several years ago and currently in progress at the Omega laser at the University of Rochester, Laboratory for Laser Energetics, has been to assess the viability of a potential noncryogenic implosion target for ignition applications at NIF. This design uses a room temperature, thin, gold inner capsule capable of holding enough gas at room temperature to ignite when driven in a staged manner by the collision of an outer shell onto the gold inner capsule. The gold wall is strong enough to support the extreme pressure needed for the required gas load without recourse to cryogenics. The penalty paid for the strong inner gold capsule is the need to compress it with a massive outer layer directly accelerated by the radiation field in the hohlraum. This is inherently a somewhat less efficient drive technique than a single-shell implosion because of the very massive set of shells involved. Figure 1 shows a double-shell design for a NIF ignition target designed for operation at a convergence ratio (CR) of 32. (This ICF target "pie" diagram should be interpreted as a section of a spherical object, indicating the various layers in that object by the horizontal lines in the drawing.) A significant further advantage to this design is that, rather than a 1:10 ratio of early foot to peak laser power, as is required for the cryogenic point design, a simple 6-ns, 300-TW, square power pulse is adequate for ignition. Such a pulse is much easier to produce and much less expensive in terms of additional active laser components than the required 1:10 NIF cryogenic-point design shaped pulse.

The key to laboratory studies of both single-shell cryogenic targets and double-shell, room-temperature targets, in an effort to determine whether they will ignite at NIF, is to get the numerical simulations to agree with experimental data. In particular, if the data can be understood in the context of simple one-dimensional (1-D) simulations, then the confidence with which one can plan ignition experiments at NIF, with 100 times more energy than current laser experiments, finally becomes sufficient to pursue particular designs. This is the stumbling block for all present-day experiments; such simple figures of merit as the total neutron yield from a 1-D calculation, when compared with the actual experimental yield, have been off by orders of magnitude at the high CRs needed to get to ignition at NIF. The task of the experimental program that is looking at double-shell implosions is to bring theory and experiment into agreement, preferably with as few modifications of the simulations away from simple 1-D behavior as possible.

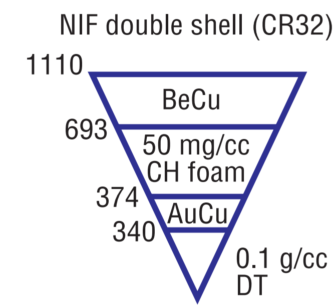

Figure 1. NIF CR 32 double-shell ignition design. This target requires a 300-TW, 6-ns square laser drive for ignition. The radial surface dimensions are in μm.

Double-Shell Target Experimental Work

The history of double-shell ICF targets is quite long. The earliest double-shell targets were fired at the Gekko XII laser in 1983, with an infrared (IR) drive and very tiny capsules, with a resultant measured yield well under 1% of that calculated by the simulation codes in use at the time. The concept fell from favor after that and lay dormant until several years ago, when a new attempt to use the double-shell target concept was started at NOVA by Los Alamos National Laboratory. As in 1983, the NOVA targets again produced poor results, with a yield compared with clean (YOC) in the 0.5%–2.5% range for a burn-averaged CR of approximately 32. Because this CR is the same as the double-shell design for NIF, this result was not very encouraging. Because the implosions were done in a cylindrical hohlraum on a laser with relatively poor energy and power balance, the belief at that time was that the thermal radiation environment uniformity was too poor to correctly drive the target, which resulted in poor performance. With this assumed degradation mechanism, better drive symmetry was assumed to be needed for successful implosions. Consequently, the concept was taken to the Omega laser at Rochester for further tests, using the tetrahedral hohlraum geometry, which was expected to produce a much better thermal drive symmetry than was the case in the NOVA cylindrical hohlraum. Examples of the various assembly stages and views of a cylindrical (NIF or NOVA style) hohlraum and the equivalent spherical (tetrahedral) hohlraum are shown in Figure 2. (The spherical hohlraum is called a tetrahedral hohlraum because the laser entrance holes are located at the four points of a tetrahedron on the surface of the sphere.)

The initial tetrahedral hohlraum double-shell implosions produced nearly identical results to the earlier NOVA data, suggesting that the thermal radiation environment was perhaps not the main culprit in the failure of these implosions. An examination of the radiation drive in the tetrahedral hohlraum indicated that about 7% of the radiation power was actually in the gold M-band in the 2–2.5 keV range. This component can be much more nonuniform than the thermal component, because of localization of the M-band source at the laser spot location, in contrast to the essentially uniform thermal radiation that comes from all locations on the inside gold wall. Because the M-band is more penetrating than the thermal component and can therefore more easily affect the inner layers of the target, we felt that the nonuniform M-band might be the culprit in double-shell implosion degradation. Consequently, we generated a new double-shell design that would be less susceptible to the M-band asymmetry. The intent of the new design was to eliminate the majority of the material present in the inner capsule that strongly absorbs the M-band (the glass in the thick-wall microballoon) and also to modify the outer surface of the inner capsule to be less unstable to the growth of instabilities driven by any nonuniformity. To accomplish this, we designed a capsule that removed 80% of the glass volume from the inner capsule and replaced that mass with a CH layer. In so doing, the outer surface of the remaining glass was tamped by an

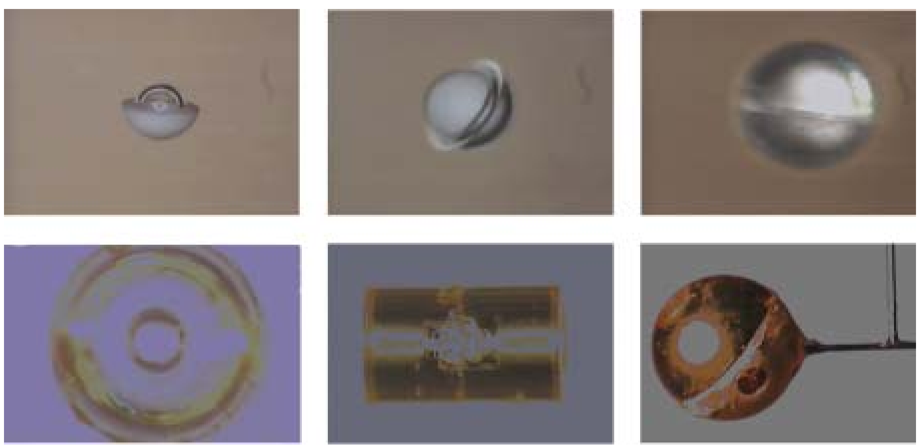

Figure 2. Images of the various stages of the assembly of the many shells in the capsule for a double-shell target, and examples of the cylindrical (NIF or NOVA style) and spherical (tetrahedral) style hohlraums used in this study. The first three images show the inner capsule surrounded successively by the foam and then the outer ablator shells. The fourth image shows the end view of a cylindrical hohlraum with such a capsule installed in it, and the fifth and sixth image are exterior views of a cylindrical and spherical (tetrahedral) hohlraum, respectively.

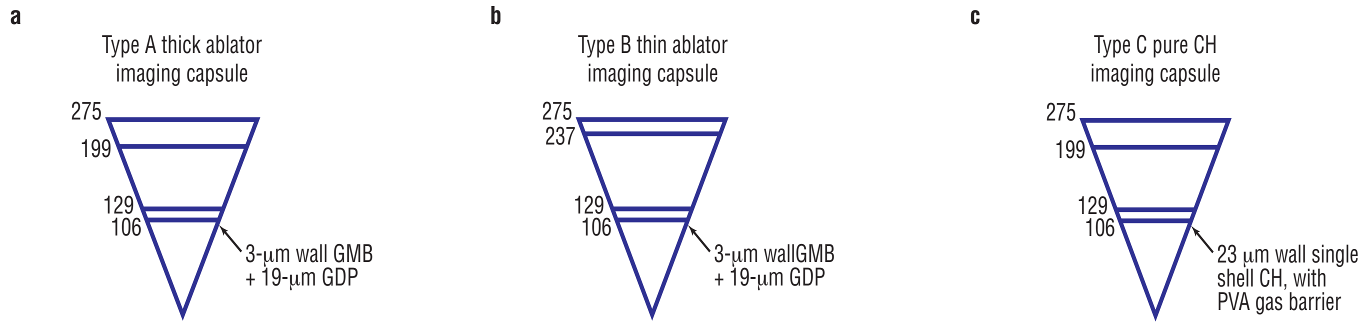

Figure 3. Three "imaging" double-shell target designs were used in the November 2000 double-shell campaign. The original-concept "imaging" target was used in both the normal ablator and in a thinned ablator variant, and a new "pure CH" "imaging" design that had the same thickness for the inner capsule, but of pure CH without the glass, provided another variation on the theme.

overcoating of CH, thus reducing its instability growth relative to that of a bare glass surface. The new unstable interface in the target, the outer surface of the inner capsule (now CH, which has a lower density than the original glass) was also less susceptible to the growth of instabilities than the original glass/ foam interface had been. This target also had the advantage that for the first time x-rays from the hot core could penetrate to the outside, and it allowed an image of the imploded core, similar in nature to the x-ray images usually taken for single-shell implosions, to be taken for this "imaging" double-shell design. Thus, the target allowed an image of the core that would both reveal any asymmetry in the imploded core directly and reduce the response of the inner capsule to any existing M-band asymmetry. The preliminary results from these targets were striking—a YOC of 40% and 60% on two shots taken in March 1999 at a CR of 32, compared with all previous work on double shells, which had a YOC <2.5%. These results were significantly better than seen in any previous CR 32 single- or double-shell implosions in the ICF program, in which typical YOC values had historically been less than 10%, regardless of the target type.

These two preliminary shots led to a full follow-up series of tetrahedral-hohlraum double-shell implosions. This follow-up series used the new design capsule at several fill pressures and consequently several different CRs. Along with the new design, this series also used the "standard" double shell. The historically poor-performing "standard" target was included in the campaign as a standard against which to measure the other designs. This series was shot in October 1999, and once again the new CH over thin-walled glass inner capsule double-shell design yielded a YOC in the 30%–70% range—verifying the earlier preliminary results, as well as this time extending those results to other higher and lower CRs.[2] As expected, the "standard" capsule again produced a poor YOC. With this confirmation that an "imaging" double-shell capsule could operate at a high YOC at a CR now well beyond that required for the NIF double-shell design, it became mandatory to determine whether the capsules would work well in a NIF-style cylindrical hohlraum. A campaign of shots was done in November 2000 to determine whether the consistently good results with the "imaging" capsule in the tetrahedral hohlraum would translate to cylinders.

The three November 2000 "imaging" double-shell variants are shown in Figure 3. Figures 3a and 3b were the original-concept thin-wall glass plus plastic over-coated "imaging" capsules, in both the original version, with its 76 micron ablator, and in a thinned-ablator (38 micron) version, which calculationally produced a much higher yield and allowed better diagnostics of the neutron production. (Experimentally, type B's yield went up significantly, allowing a measurement of the secondary DT neutrons for the first time.) Figure 3c was another new-design "pure CH" imaging capsule, which removed the remaining glass from the central capsule. We placed a constraint on the target-fabrication team in MST-7 that we would not accept any targets with visible external imperfections. Detailed examination of the targets showed them to be essentially visually perfect.

Results

This final campaign using indirectly driven double-shell targets in ICF was designed primarily to determine whether the favorable performance seen in the "imaging" double shells in tetrahedral hohlraums would translate to NIF-style cylindrical hohlraums. The plot of YOC vs CR for the deuterium-filled capsules of all "imaging" variants for all shots, both tetrahedral and NIF style, shown in Figure 4, indicates that the performance in either type of hohlraum is comparable. In all cases, the performance of the "imaging" CH-over-glass double-shell design approaches that of a clean 1-D simulation.

Additionally, although the results have more spread than desired, the new pure-CH capsules also worked well in the NIF-style hohlraum. This suggests that preheat decompression caused by x-ray absorption in the remaining glass part of the "imaging" capsule and its resulting effect on the implosion dynamics, which are somewhat different for the pure-CH and the CH-over-glass "imaging" capsules, while it probably plays a role, is not mandatory for good performance. (It may be that the very reproducible results at a given CR for the CH-over-glass "imaging" capsules, as opposed to the somewhat larger data spread seen for the pure-CH capsules, is connected to this). Static x-ray images of the imploded cores of all the new-design "imaging" capsules in November 2000 indicated an essentially round time-integrated implosion, consistent with the good performance of these capsules. Figure 5 shows an 80-ps frame from an implosion of the "imaging" capsule shot in October 1999.

Finally, for the first time in this experimental campaign, a successful set of density-radius measurements was returned. As mentioned in the introduction, in order to reach ignition, it is critical to have a long enough path at high density to absorb the alpha particles from the DT reaction before they escape the core. As in the case of the yield figure of merit, it is necessary to show that the simulations are producing density-radius product values close to that measured in order to have confidence in the calculational tools. The density-radius product values calculated for this set of shots ranged from 6 to 9 as did the measured values, which suggests that the simulations are getting this correct, and nothing about the real implosion is radically different from 1-D behavior, the same conclusion arrived at from the measured yield.

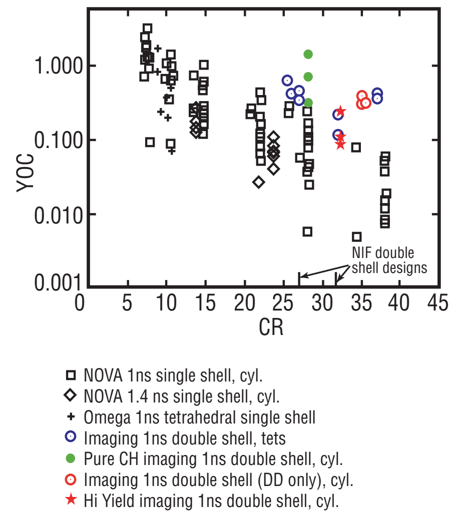

Figure 4. YOC vs CR for all Omega imaging and pure-CH DT shots to date, in tetrahedral and NIF-style hohlraums. The data for NIF-style hohlraums is shown in shades of red, while the tetrahedral results are in shades of blue. The DT-filled capsules used in November are not shown because of remaining uncertainties in the gas fill. In the legend, cyl is a cylindrical hohlraum, tet is a tetrahedral.

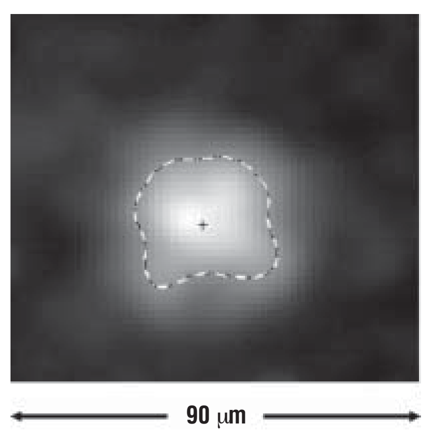

Figure 5. An 80-ps-duration x-ray image of an imploded core at minimum radius for a CH-over-glass "imaging" capsule.

Conclusions

The type of hohlraum used for an indirect-drive, double-shell implosion, given high-quality targets and an "imaging"-type capsule design, seems to be unimportant. The behavior of "imaging" double shells, regardless of whether they contain glass or not in their inner capsule, seems to significantly exceed the performance of comparably sized single-shell capsules. Both the pure-CH and the CH-over-glass "imaging" capsules approach clean 1-D performance at calculated CRs well beyond that required for an ignition double-shell design to work at the original NIF energy level. The agreement between the measured and calculated density-radius product values indicates that use of the calculated CR in the comparison with prior YOC data is a valid one. This means that the double-shell concept remains a viable alternative to cryogenic single-shell ignition target designs for NIF.

References/For Further Reading

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[2] W. S. Varnum, N. D. Delamater, S. C. Evans, P. L. Gobby, J. E. Moore, J. M. Wallace, R. G. Watt (LANL), J. D. Colvin, R. Turner (LLNL), V. Glebov, J. Soures, C. Stoeckl (UR/LLE), *Physical Review Letters* 84, 5153 (2000).